Experimental Studies and Lunar Simulant Requirements

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Premise

- Better understand the sintering, melting, and crystallization behavior of lunar materials for construction
- Unique properties regolith that affect these behaviors
- Experimental studies of lunar regolith and basalt can provide some insight
- Additional studies to determine the sintering behavior
- Can these studies be done with simulants or are lunar materials necessary?

Definitions

Sintering

- Temperatures between the glass transition and solidus, no melting
- Limited variation is physical properties with porosity being one of the important ones
- Physical properties vary with time and temperature of sintering, grain size, composition, and physical state of the soil

Melting

- Temperatures above the solidus
- Some melting can reduce porosity and increase strength

Definitions

Crystallization

- Can produce a custom product.
- Complex and variable process can produce a variety of physical properties
- Tailoring the physical properties to desired uses requires extensive experimentation
- Tensile strength, surface toughness, resistance to fracturing, and insulation properties could all be controlled

Previous Experimental Studies

- A dynamic crystallization study of lunar soil 15101 demonstrated melting and crystallization properties
- Showed how to vary textures and obtain final products with differing physical properties
- Variations in melting temperatures and time followed by crystallization at different cooling rates
- Oxygen fugacity is IW-1 log unit, Fe^{o} stable. Atm controlled with appropriate ratio of CO/CO_2
- This was not a study of physical properties and none were measured

	15101[1]	14259[2]	14310[3]	POIKILITIC ROCKS[4]
SiO_2	46.21	48.16	48.82	44.7 - 47.0
TiO_2	1.31	1.73	1.16	0.7 - 1.7
Al_2O_3	17.56	17.60	20.50	17.2 - 22.9
Cr_2O_3	0.28	0.26	0.07	NOT REPORTED
FeO	11.61	10.41	7.69	7.1 - 10.5
MnO	0.16	0.14	N.D.	0.07 - 0.13
MgO	10.32	9.26	7.78	9.9 - 13.2
CaO	11.63	11.25	12.51	10.4 - 13.3
NaO_2	0.40	0.56	0.60	0.3 - 0.6
K_2O	0.18	0.61	0.39	0.1 - 0.4
P_2O_5	0.16	0.53	N.D.	0.2 - 0.5
S	0.07	N.D.	N.D.	NOT REPORTED
TOTAL	99.89	100.51	99.51	

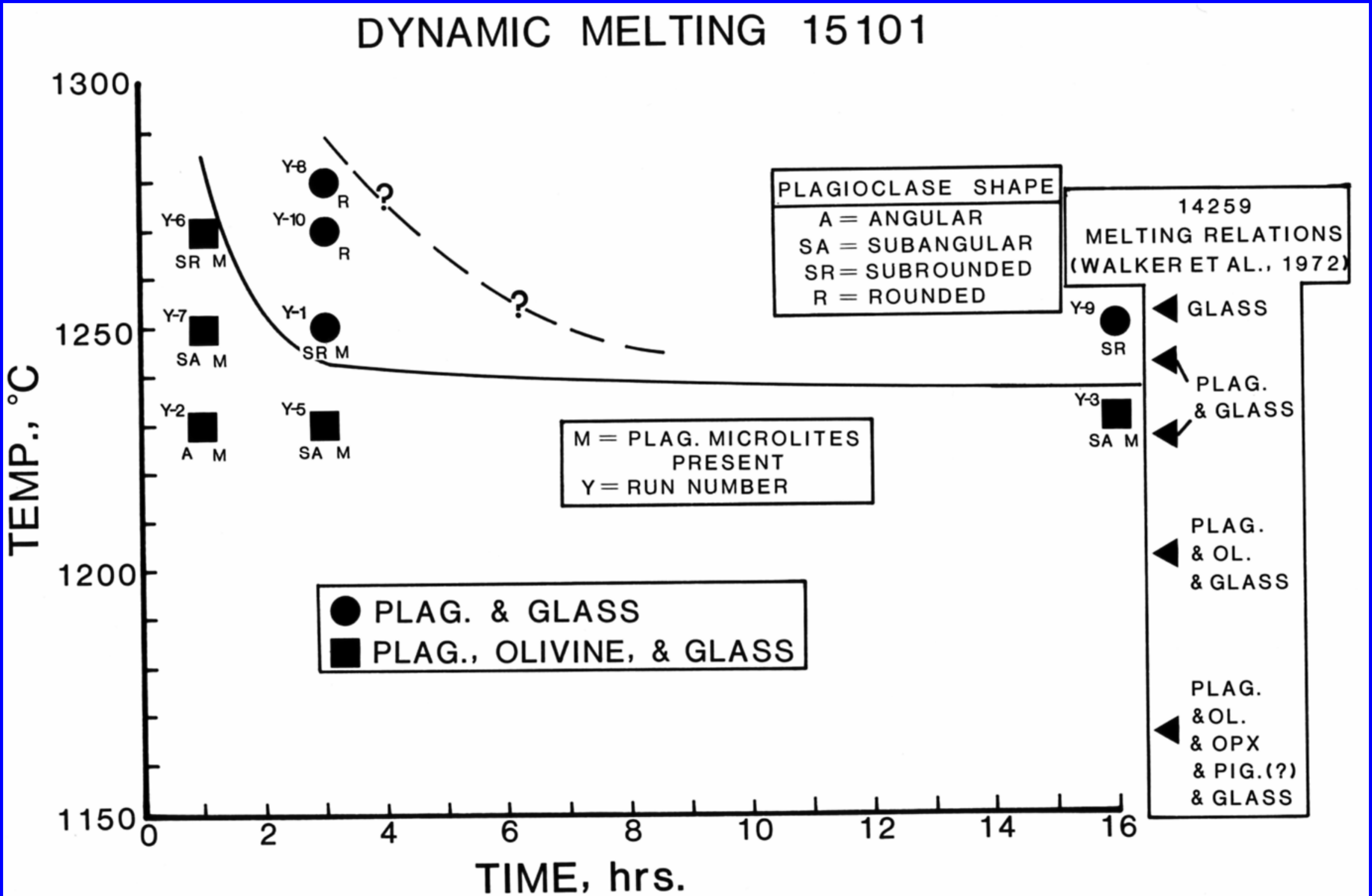
[1] AVERAGE OF 4 XRF ANALYSES
[2] ROSE ET AL. (1972)
[3] SYNTHETIC 14310, LOFGREN (1977)
[4] SIMONDS ET AL. (1973)

Average Lunar Soil compositions from the Bible

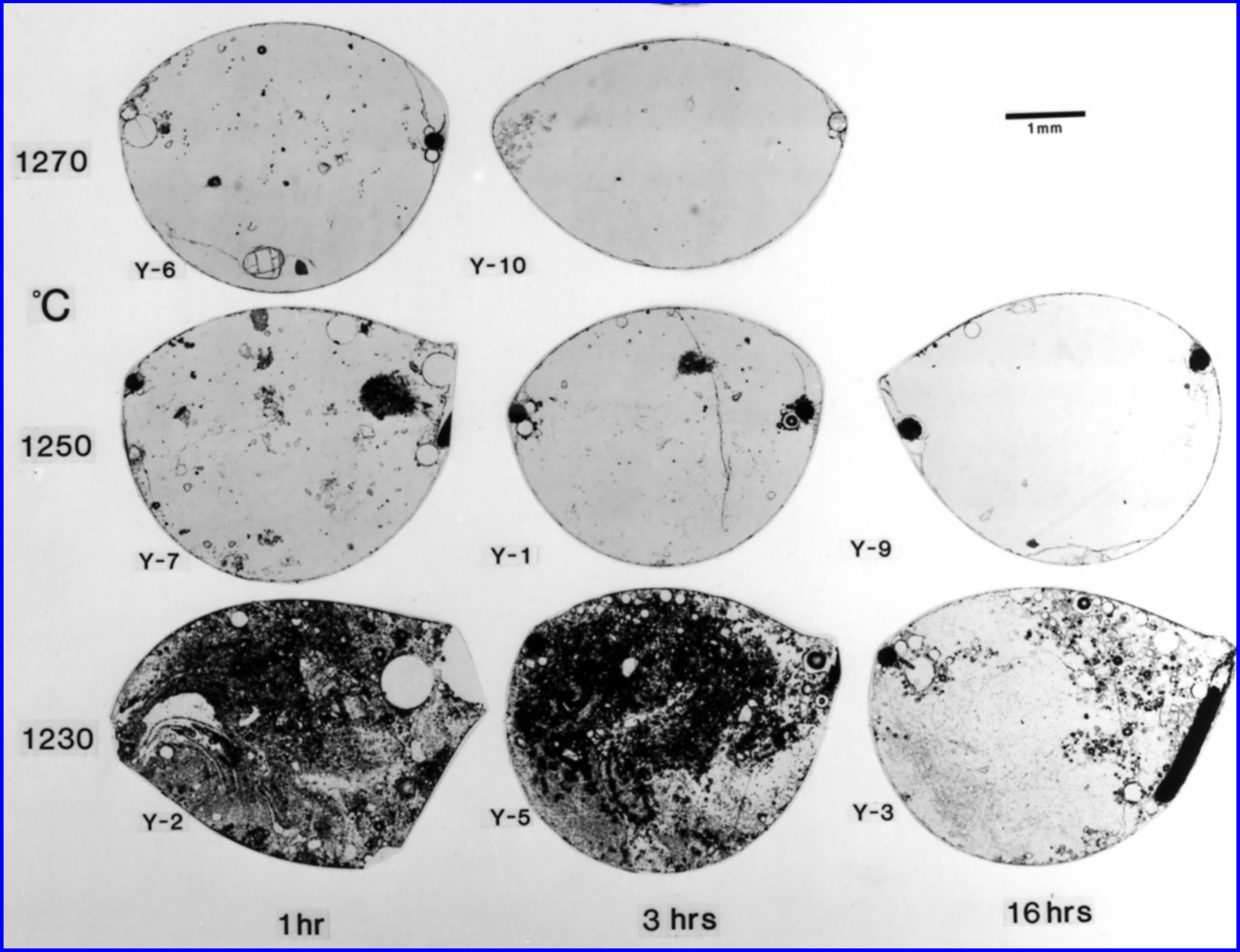
	11	12	14	15a	15b	15c	15
SiO_2	42.2	46.3	48.1	46.7	46.6	47.1	46.8
TiO_2	7.8	3.0	1.7	1.7	1.4	1.0	1.4
Al_2O_3	13.6	12.9	17.4	13.2	17.1	13.4	14.6
Cr_2O_3	0.30	0.34	0.23	0.44	0.27	0.37	0.36
FeO	15.3	15.1	10.4	16.3	11.7	14.9	14.3
MnO	0.20	0.22	0.14	0.21	0.16	0.19	0.19
MgO	7.8	9.3	9.4	10.9	10.5	13.0	11.5
CaO	11.9	10.7	10.7	10.4	11.6	10.3	10.8
Na_2O	0.47	0.54	0.70	0.38	0.45	0.33	0.39
K_2O	0.16	0.31	0.55	0.23	0.20	0.19	0.21
P_2O_3	0.05	0.4	0.51	0.16	0.19	0.19	0.18
S	0.12	—	—	0.07	0.08	0.04	0.06
Total	99.9	99.6	99.8	100.6	100.2	100.9	100.8

Average Lunar Soil compositions from the Bible

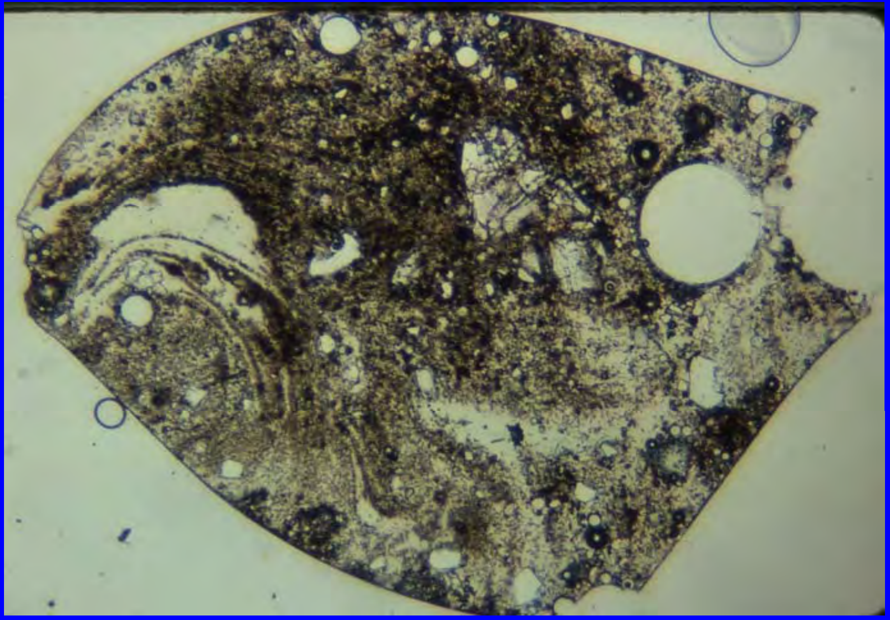
	16a	16b	16c	16	17a	17b	17c	17d	17
SiO_2	45.0	44.9	45.1	45.0	40.6	45.1	43.5	43.7	43.2
TiO_2	0.56	0.47	0.60	0.54	8.4	1.7	3.4	3.5	4.2
Al_2O_3	27.1	28.0	26.8	27.3	12.0	20.7	18.0	17.4	17.1
Cr_2O_3	0.34	0.54	0.11	0.33	0.45	0.25	0.28	0.32	0.33
FeO	5.2	4.7	5.4	5.1	16.7	8.8	10.9	12.2	12.2
MnO	0.41	0.27	0.22	0.30	0.23	0.12	0.16	0.16	0.17
MgO	5.8	5.6	5.7	5.7	9.9	9.8	10.7	11.1	10.4
CaO	15.8	15.7	15.6	15.7	10.9	12.8	12.12	11.3	11.8
Na_2O	0.46	0.50	0.43	0.46	0.35	0.42	0.42	0.42	0.40
K_2O	0.13	0.23	0.14	0.17	0.16	0.16	0.12	0.09	0.13
P_2O_3	0.13	0.10	0.10	0.11	0.14	0.15	0.09	0.08	0.12
S	0.07	0.05	0.09	0.07	0.12	0.09	0.07	0.09	0.09
Total	100.9	100.9	100.4	100.8	100.1	100.0	99.8	99.9	100.5



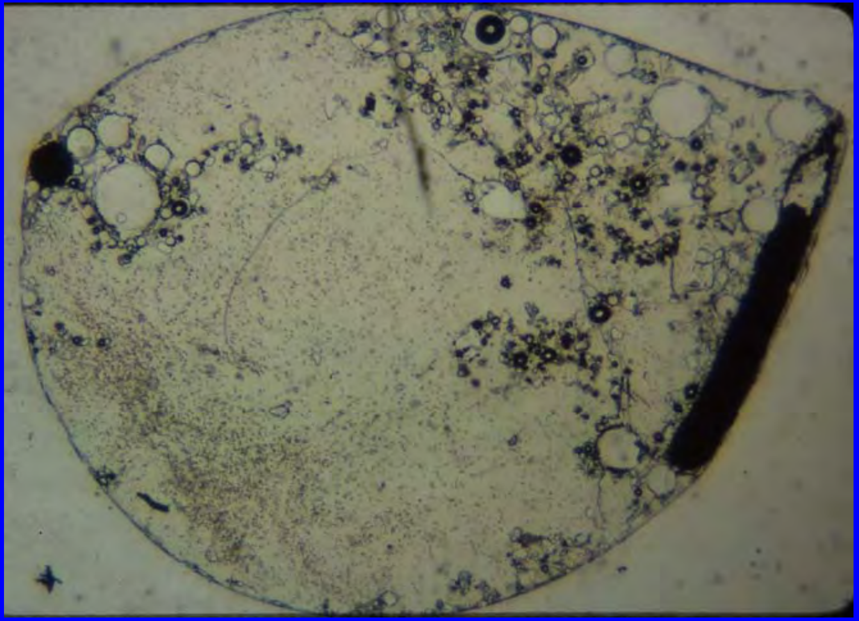
DYNAMIC MELTING 15101
1300
1250
1200
1150
TEMP., °C
0
2
4
6
8
10
12
14
16
TIME, hrs.
Y-8
R
Y-10
R
Y-6
SR M
Y-7
SA M
Y-1
SR M
Y-2
A M
Y-5
SA M
?
?
PLAGIOCLASE SHAPE
A = ANGULAR
SA = SUBANGULAR
SR = SUBROUNDED
R = ROUNDED
14259
MELTING RELATIONS
(WALKER ET AL., 1972)
Y-9
SR
Y-3
SA M
GLASS
PLAG.
& GLASS
PLAG.
& OL.
& GLASS
PLAG.
& OL.
& OPX
& PIG. (?)
& GLASS
M = PLAG. MICROLITES
PRESENT
Y = RUN NUMBER
PLAG. & GLASS
PLAG., OLIVINE, & GLASS


1270
°C
1250
1230
Y-6
Y-10
Y-7
Y-1
Y-9
Y-2
Y-5
Y-3
1mm
1 hr
3 hrs
16 hrs

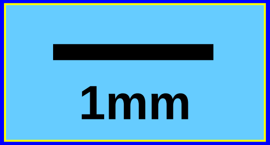
Melting Textures

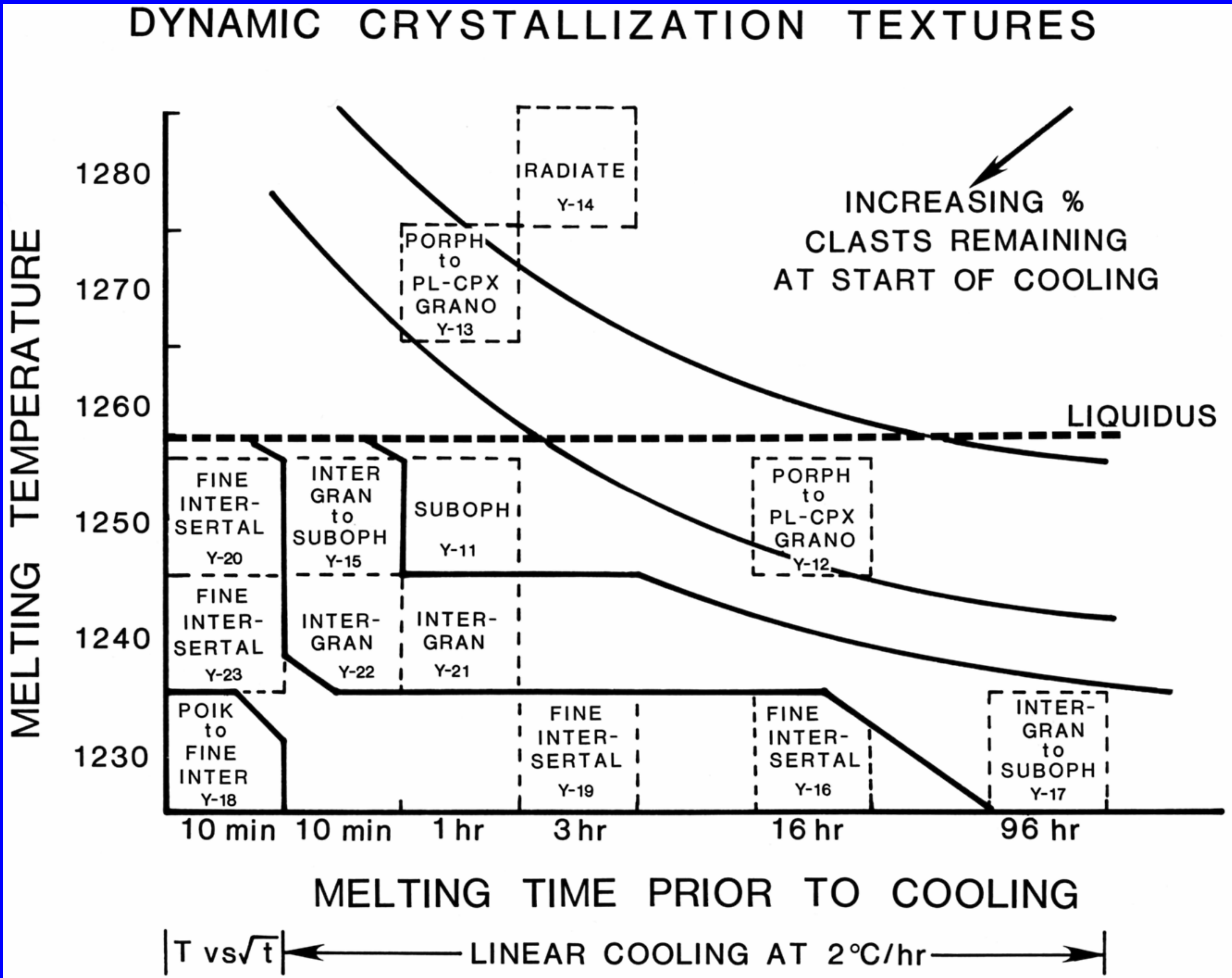


Melt 1230ºC for 1 hr

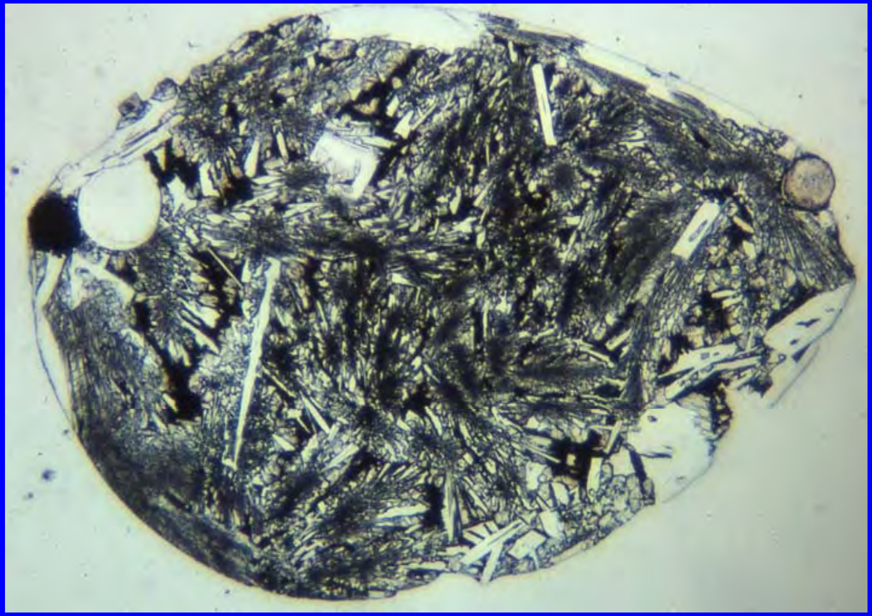


Melt 1230ºC for 16 hrs

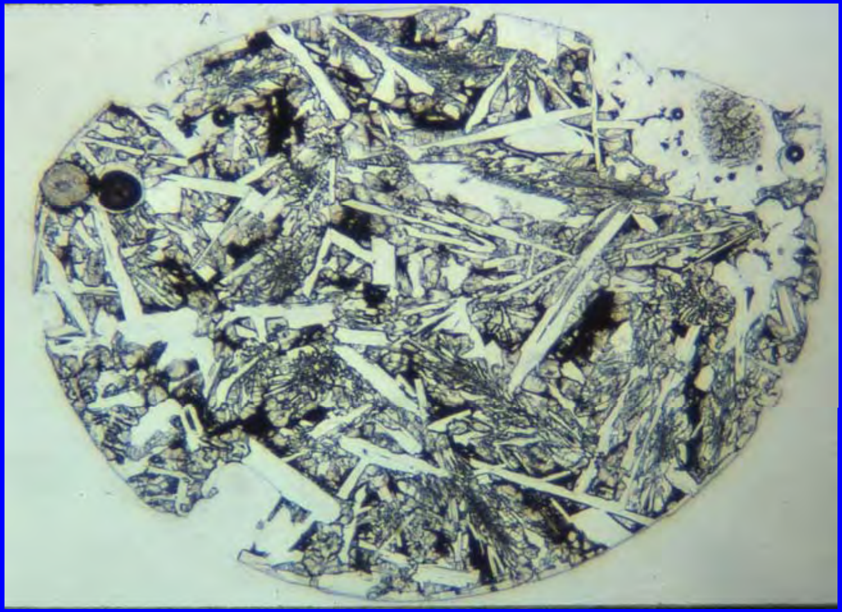



DYNAMIC CRYSTALLIZATION TEXTURES
MELTING TEMPERATURE
1280
1270
1260
1250
1240
1230
RADIATE Y-14
PORPH to PL-CPX GRANO Y-13
INCREASING % CLASTS REMAINING AT START OF COOLING
LIQUIDUS
FINE INTER-SERTAL Y-20
INTER GRAN to SUBOPH Y-15
SUBOPH Y-11
PORPH to PL-CPX GRANO Y-12
FINE INTER-SERTAL Y-23
INTER-GRAN Y-22
INTER-GRAN Y-21
POIK to FINE INTER Y-18
FINE INTER-SERTAL Y-19
FINE INTER-SERTAL Y-16
INTER-GRAN to SUBOPH Y-17
10 min
10 min
1 hr
3 hr
16 hr
96 hr
MELTING TIME PRIOR TO COOLING
T vs√t
LINEAR COOLING AT 2°C/hr

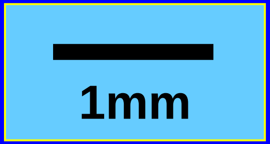
Crystallization Textures

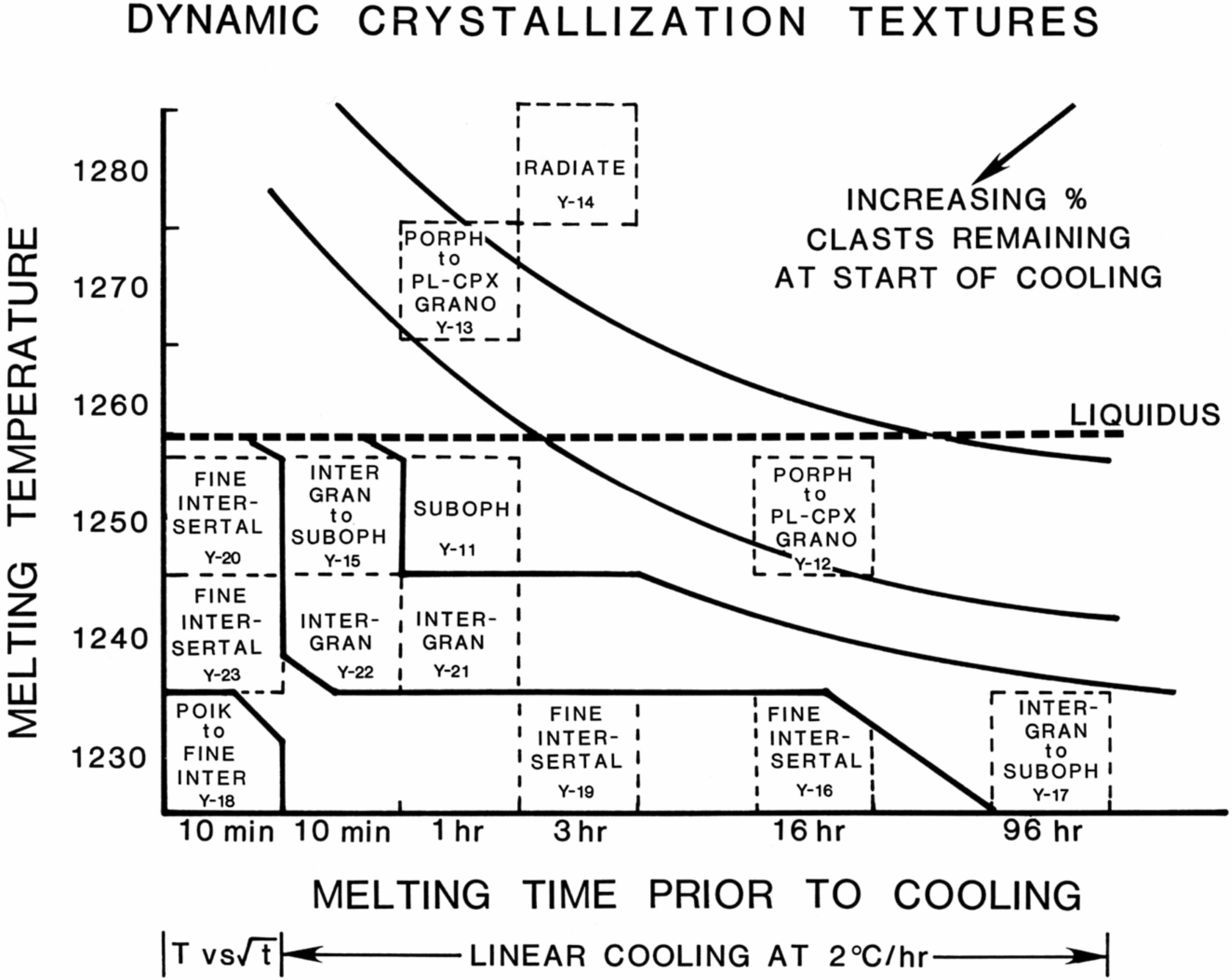


Melt1280°C 3 hrs
Cool 2°C/hr



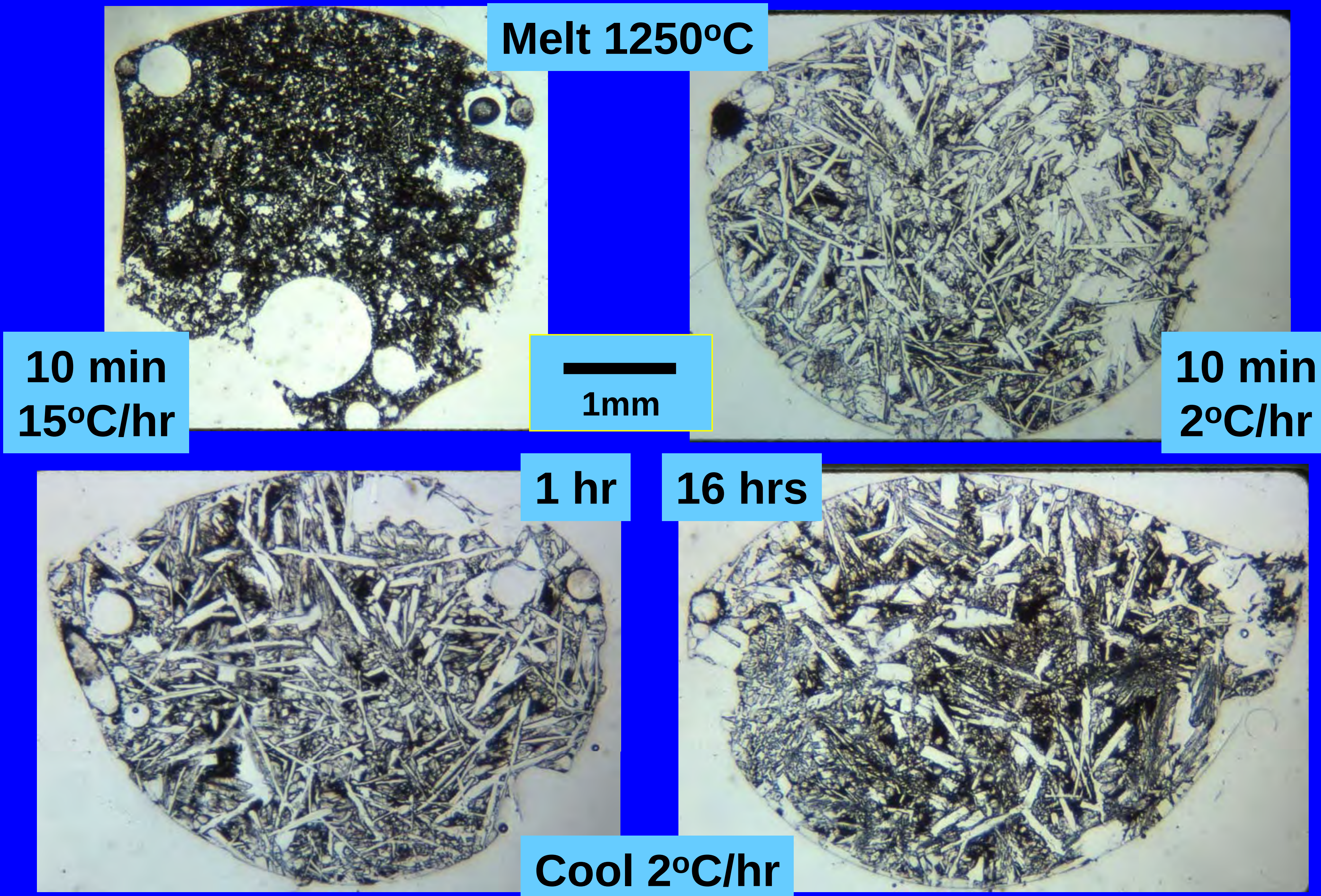
Melt1270°C 1 hr
Cool 2°C/hr



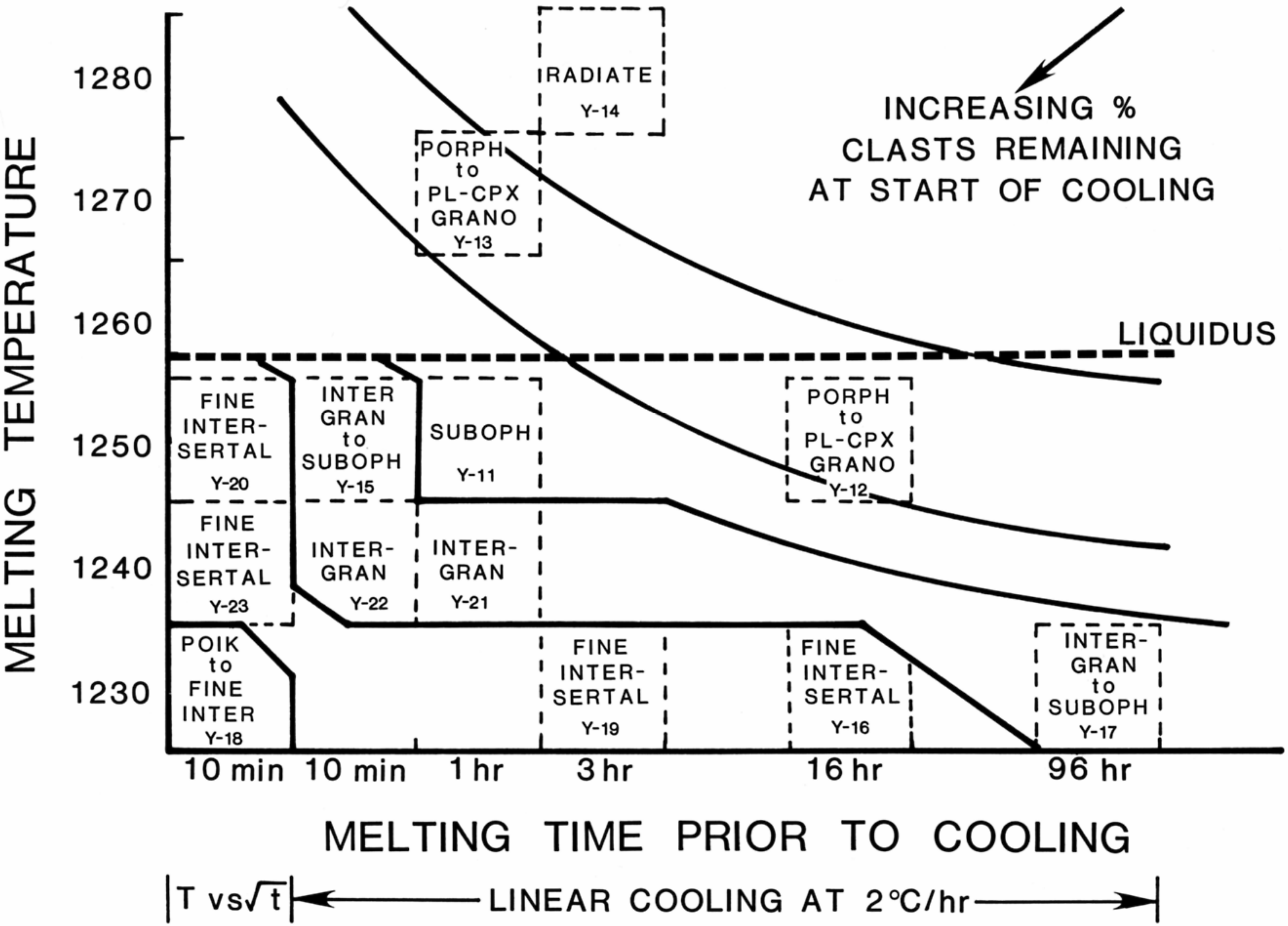


DYNAMIC CRYSTALLIZATION TEXTURES
MELTING TEMPERATURE
1280
1270
1260
1250
1240
1230
RADIATE
Y-14
PORPH to PL-CPX GRANO
Y-13
INCREASING % CLASTS REMAINING AT START OF COOLING
LIQUIDUS
FINE INTER-SERTAL
Y-20
INTER GRAN to SUBOPH
Y-15
SUBOPH
Y-11
PORPH to PL-CPX GRANO
Y-12
FINE INTER-SERTAL
Y-23
INTER-GRAN
Y-22
INTER-GRAN
Y-21
POIK to FINE INTER
Y-18
FINE INTER-SERTAL
Y-19
FINE INTER-SERTAL
Y-16
INTER-GRAN to SUBOPH
Y-17
10 min
10 min
1 hr
3 hr
16 hr
96 hr
MELTING TIME PRIOR TO COOLING
T vs√t
LINEAR COOLING AT 2°C/hr

Crystallization Textures



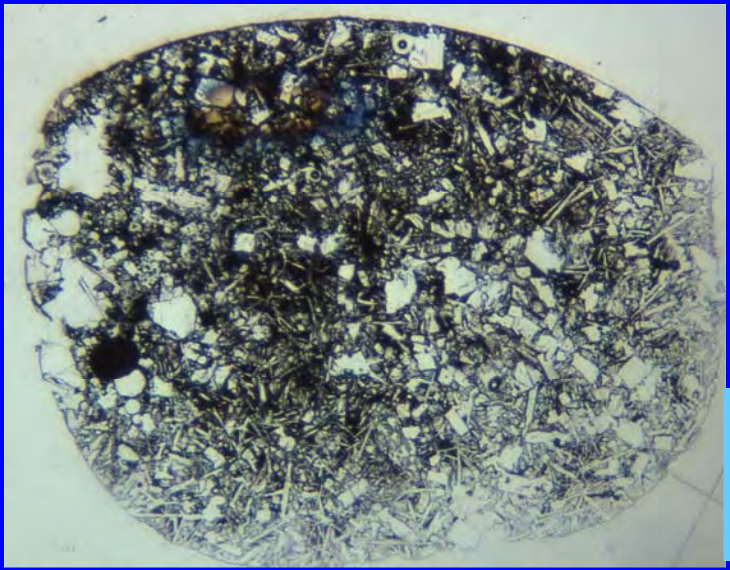
DYNAMIC CRYSTALLIZATION TEXTURES



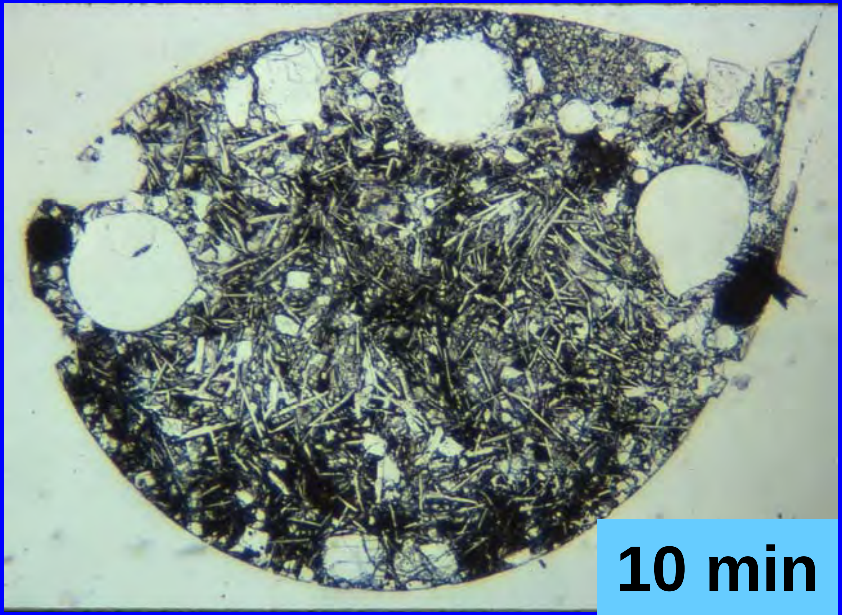
Crystallization Textures

Melt 1240^{o}C

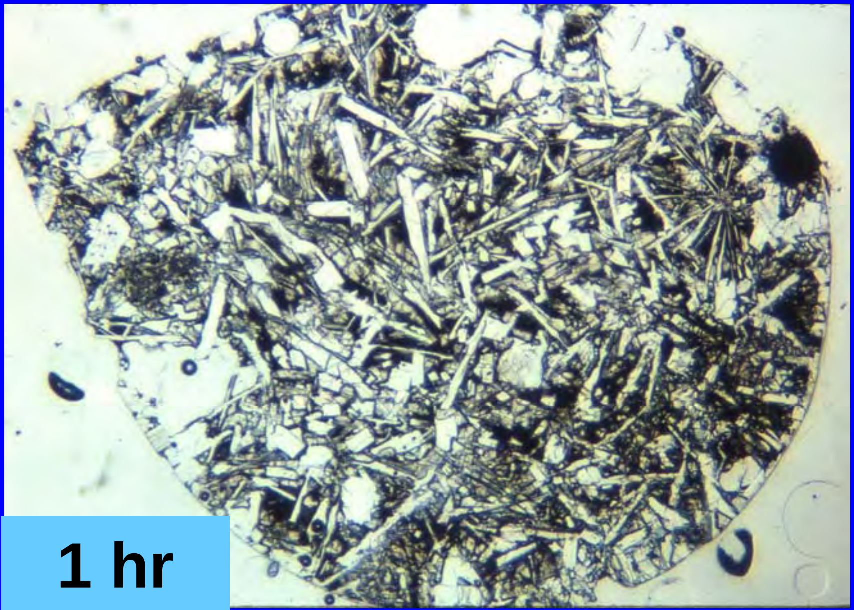
1mm



10 min
9^{o}C/hr

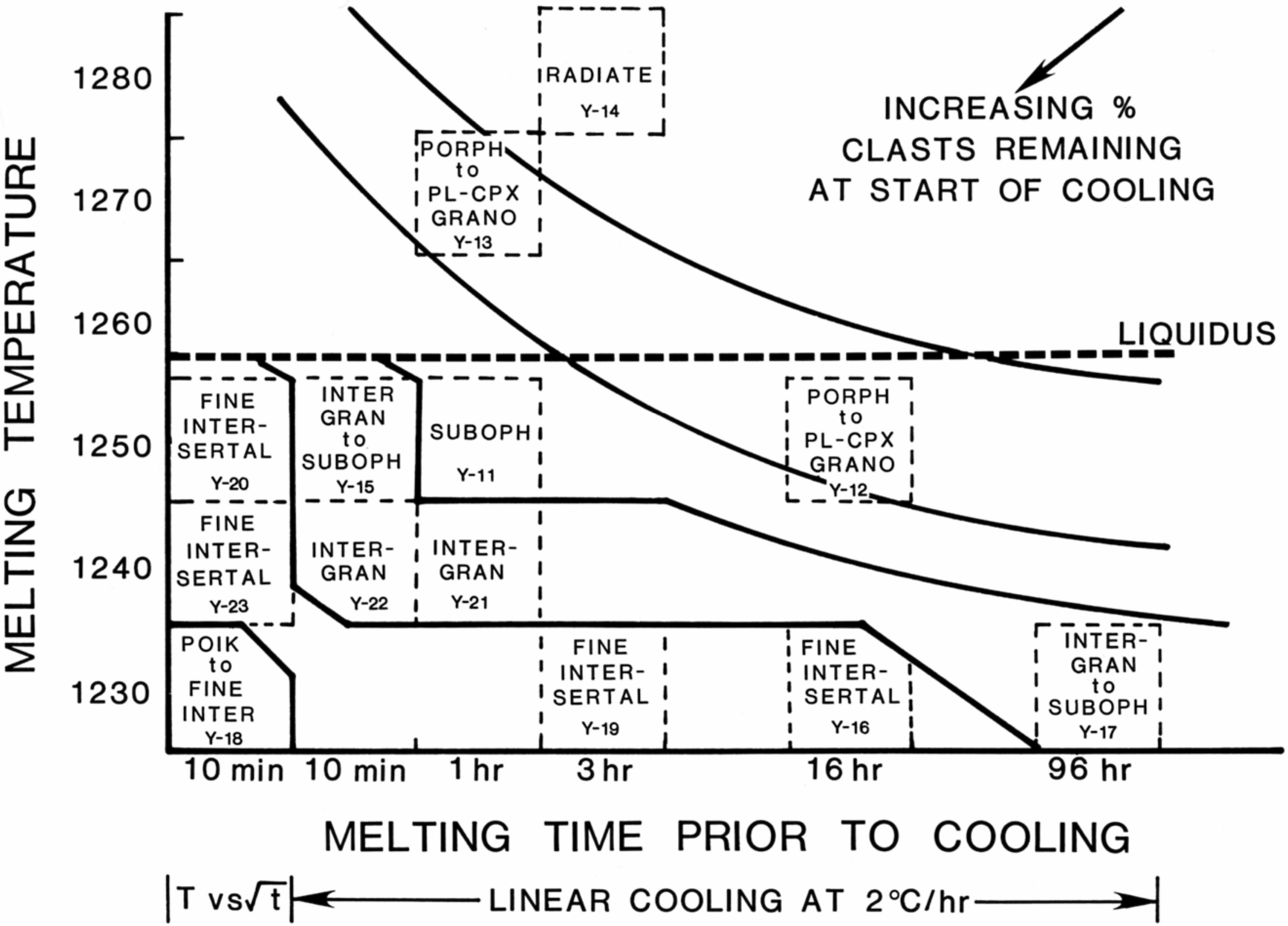


10 min
2^{o}C/hr



1 hr
2^{o}C/hr

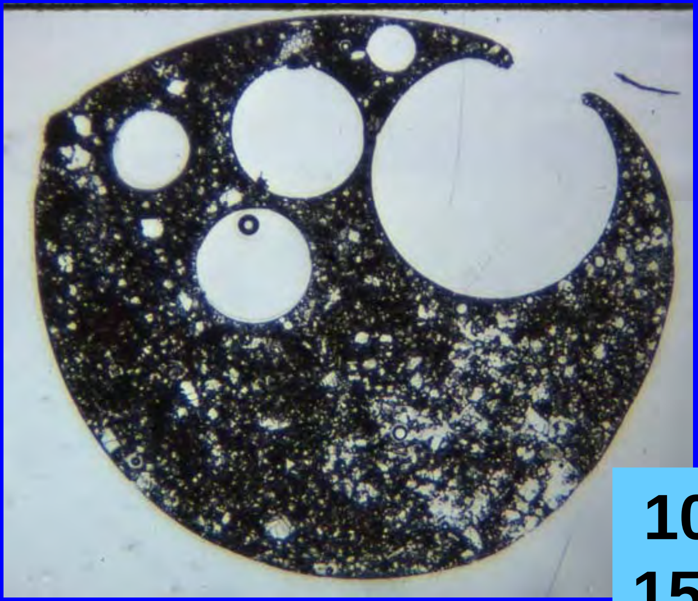
DYNAMIC CRYSTALLIZATION TEXTURES



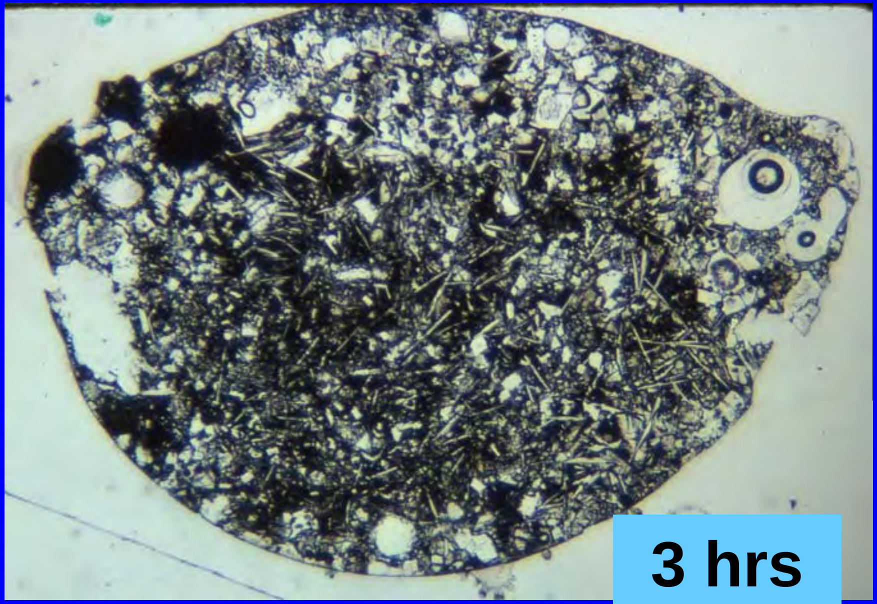
Crystallization Textures

Melt 1230^{o}C

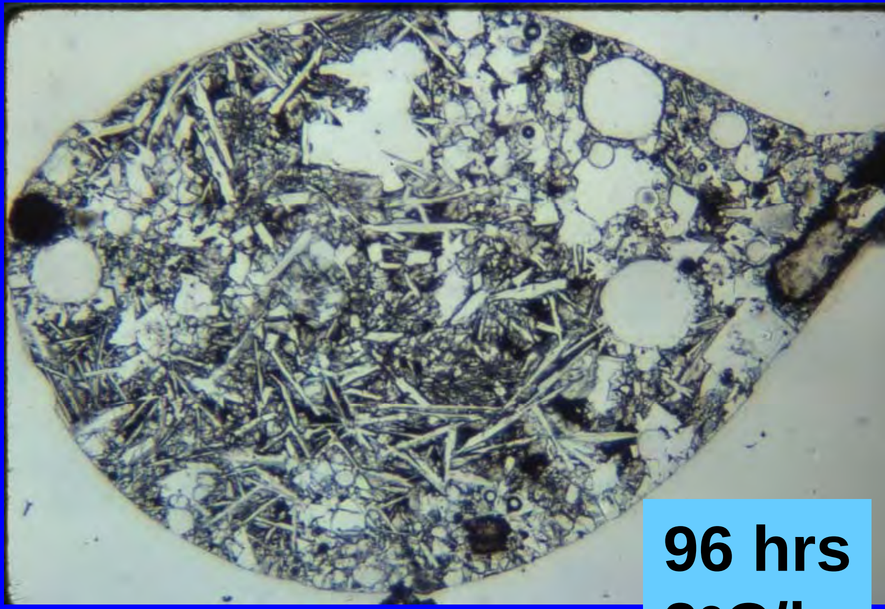
1mm



10 min
15^{o}C/hr

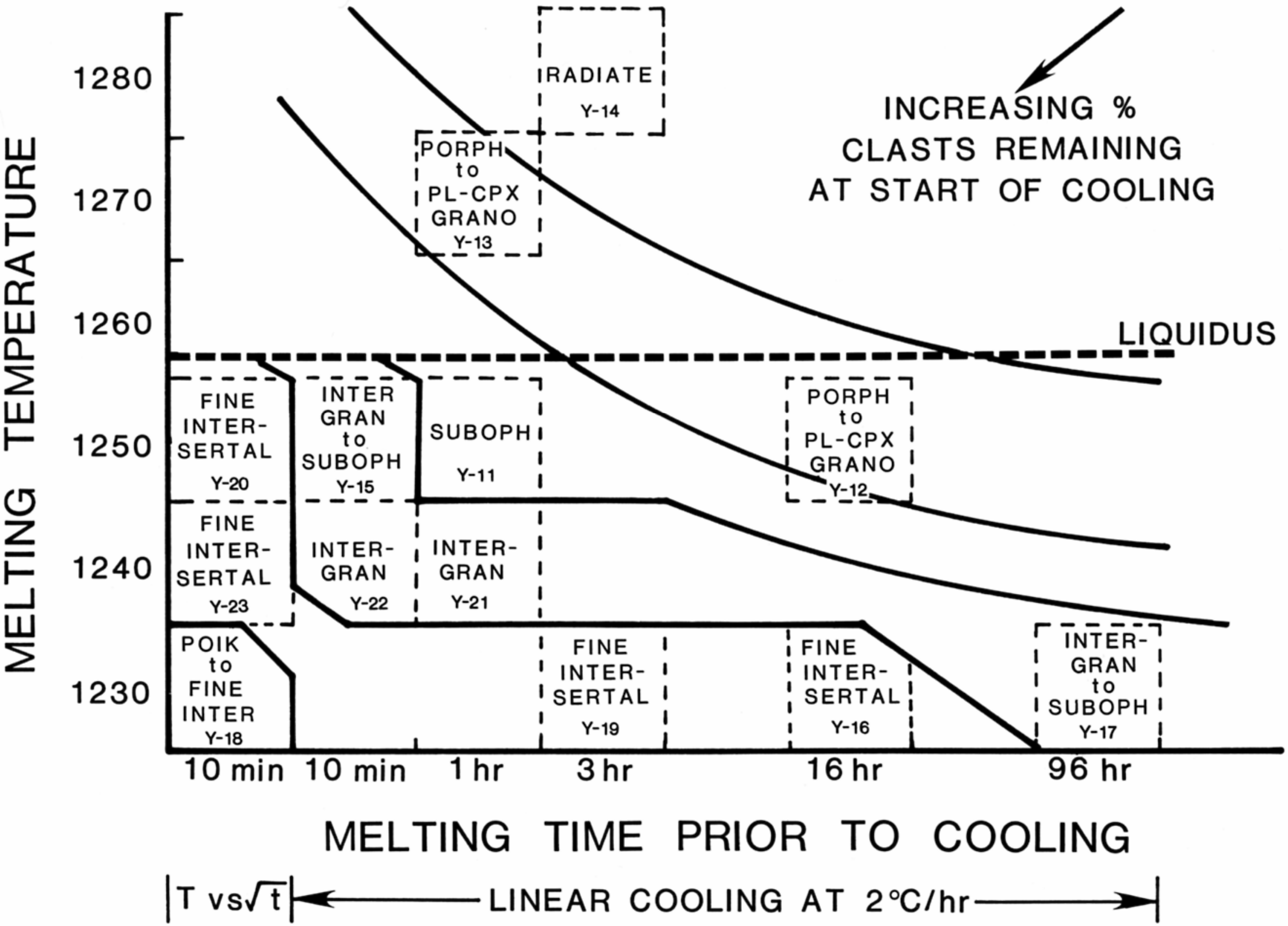


3 hrs
2^{o}C/hr



96 hrs
2^{o}C/hr

DYNAMIC CRYSTALLIZATION TEXTURES



The Best Lunar Regolith for Processing

- Regolith with the lowest solidus temperatures
- Regolith with the largest fraction of finer grain sizes
- Regolith with high glass content, either agglutinates or spheres and fragments
- Glass content is not as important for melting and crystallization processes

Important Regolith Properties

- Bulk composition--controls the solidus temperatures
- Glass and agglutinate content—ease of sintering
- The unique grain size distribution, with emphasis on mature soils—ease of sintering and melting
- Experimental studies require a faithful simulant, but not large quantities
- Some experiments could be done with small amounts of lunar regolith
- Extensive physical testing requires large a amount of simulant

Energy Requirements

- The energy to produce melting and crystallization is significant
- Use solar collectors with stored power with a conventional furnace or a microwaves
- Another possible source is direct solar power such as a solar furnace that uses focused sunlight

Sources of Information

- Basalt has been used extensively as the raw material for casting ceramic products in Eastern Europe in the early 20th century
- This industry provides insight into sintering and crystallization histories necessary to produce desired physical properties
- The US ceramic industry has extensive experience with sintering of silicate materials